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RESEARCH ON A MANUALLY PILOTED AIRBORNE ZERO-ZERO LANDING SYSTEM

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INTRODUCTION

The interest of Ames in the zero-zero landing problem grew out of research work related to the development of STOL aircraft and the supersonic transport. Both of these vehicles should have the ability to operate under zero-zero conditions if their full value is to be realized. Part of the research work on these vehicles is a detailed study of the handling qualities required to assure satisfactory control during approach and landing. Because advanced - and not yet flying - aircraft can be studied only through the simulation technique, Ames has developed a considerable effort in this direction. Simulation, by definition, requires artificial presentation of apparently real situations. Since wholly real environment cannot be supplied in a simulator, it has been necessary to examine carefully those factors important in the real environment which must be reproduced if the simulator is to provide favorable results. It has been found that comparable results in the evaluation of approach and landing problems for the same vehicle on the simulator and in flight can be obtained with relatively symbolic presentation of outside world visual information on the simulator. This result led Ames Research Center to consider specifically the possibility of generating a symbolic display

which could substitute adequately for VFR information and enable a zero-zero landing to be made in exactly the same manner as a VFR landing. Achievement of such a display would, of course, be a major step in the realization of a zero-zero landing capability and toward satisfying the operational requirements of the supersonic transport and STOL aircraft under study.

Certainly, Ames is not alone in recognizing this requirement - a fact attested to by the many research organizations and equipment manufacturers developing zero-zero landing systems. Many of these are extensions of existing landing aids to permit automatic or semiautomatic flare and touchdown. This is a logical, evolutionary process which allows incorporating into current operations each increment of progress toward zero-zero operation. Most of these systems will require a minimum of airborne equipment - a desirable, reasonable requirement for current conditions because carrier operations are almost exclusively from large, well equipped fields which can support extensive ground installations. In addition, field equipment can be installed without interrupting normal service; this would not be true if a whole change to airborne systems were undertaken. To make a useful contribution to this evolutionary development requires a close association with day-to-day operations, an association not characteristic of a research center. Rather, because it is relatively independent of the economics of day-to-day commercial operations, Ames Research Center has the freedom, as well as a responsibility, to investigate systems with longer range applications and of a more revolutionary character.

OBJECTIVES OF THE AMES PROGRAM

Ames has undertaken a study of the zero-zero landing problem which is intended to fulfill two special requirements; first, to provide a display with which the pilot can land the airplane, making the same judgments, coming to the same conclusions, and applying the same control techniques that he does during visual landings; and second, to install the sensing and the display-generating equipment on board the airplane, with the minimum possible ground-based equipment.

We argue in support of these requirements as follows: a manual zero-zero landing system should not require all of the equipment implied in an automatic system. Further, a display which allows the pilot to land the airplane as he does under visual conditions need contain no director or command information, and therefore, the equipment to compute such information would not be needed. Because fewer components are necessary for a fully manual system than for an automatic or a semiautomatic (defining as semiautomatic a system with command information in the display), it is reasonable to suppose that the manual system would weigh less, be much less complex, and, it follows, cheaper and more reliable. Finally, and probably most important, such a system would maintain the pilot at peak proficiency in the performance of this most critical maneuver; this in opposition to the automatic or semiautomatic system where the pilot is required to perform in only the least demanding conditions.

We propose that the system components be airborne because such an arrangement would allow the use of many landing places which, for one reason or another, cannot support large ground installations. This is a

capability of only indirect advantage in international commercial operations. But it could be of great benefit to short haul, commuter airlines operating from small airports, for if no ground equipment were necessary, any airport with an adequate runway could become a stopping point. The military too could make good use of an airborne system for operating in and out of unprepared areas.

The problems to be solved and the questions to be answered in developing a display and defining the pilot's role are of general concern to any all-weather operation. For example, is it possible to replace the pilot's view of the outside world in a way which enables him to gather the same information and come to the same conclusions he does under VFR conditions? If so, can he make zero-zero landings routinely as he does VFR, unaided by electronics except for information gathering and display? Or must there be at least some electronic decision making? Or is an automatic system unavoidable? Do the display requirements depend on whether the pilot does the flying, shares duties with, or only monitors an automatic system?

The Ames research program, it is hoped, will provide answers to questions such as those in the preceding paragraph and will result in the development of a display which will provide the following capabilities. The pilot must be able to land conventional, as well as STOL airplanes, responding to the display in the same way he responds to the outside world under VFR conditions. He should be able to cope with adversities, such as gusts, cross winds, and bounces. This implies that he have also the extra information according to which he plans to wave off should the

landing deteriorate. The display must allow him to recognize deterioration in the landing at least as well as he can recognize it during visual landings. He must be able to use the display in conjunction with VFR landings, and in that way develop confidence in the system and gain and maintain experience and proficiency in its use. Also, the display must minimize - to zero if possible - ambiguity or discord during transition from IFR to VFR under not quite zero-zero conditions.

Several companies in the aviation electronics field are developing systems with some degree of similarity to the one we have proposed. Three such are the Sperry Windshield Display by the Sperry Gyroscope Company, the Microvision system under development by the Bendix Corporation, and the Microwave Remote Area Instrument Landing System, called MW RAILS, developed by the Bell Helicopter Company. Collectively, these systems provide many of the requirements we have listed. Our goal is to satisfy these requirements in one display.

Effects of Limited Angle of View

Two-Dimensional Vision

As a first step toward the manual zero-zero landing we conducted a program to study the feasibility of two-dimensional, VFR-like displays, and to determine whether factors exist which might preclude their successful use. To do this we equipped a R4D transport airplane with a closed-circuit TV system which presents the pilot with a contact analog display of the normal view forward through the windscreen. Flight tests have been conducted to compare normal visual landing conditions with the television display and with the condition where the pilot viewed the real world through a masking reticle having the same visual angle as the TV display.

We found it possible to make landings using the TV display; however, there is an increase in pilot effort and, even with the best picture, a definite decrease in the ability to judge changing flight path conditions. Visual landings were made with greater ease using the masking reticle which gave the same visual angle as the television picture.

Results of these tests suggested that a two-dimensional display is not inherently impractical. It was concluded, however, that a two-dimensional display can be improved by symbolic means to compensate for marginal or missing cues and provide zero-zero landing capability.

Aircraft Simulation Equipment

Obviously it is difficult to undertake both display and system research simultaneously using an actual aircraft. The use of simulation equipment avoids this problem very handily. Display development can be carried out, with pilot participation, on a landing simulator without concern for the system that generates the display; all of the required display information can be extracted readily from a computer, since the computer can supply all of the information needed to describe the aircraft situation. At the same time, all of the various airborne systems capable of generating a display can be synthesized and simulated on a computer without actual hardware so that system stability, error analysis, etc., can be investigated. In this way concurrent studies can proceed without interference but the knowledge gained in each phase can be absorbed immediately into the other.

As noted in the introduction, Ames has been developing and using simulators to study the approach and landing problem and has reached a

stage where this is being accomplished satisfactorily. It was a simple step, therefore, to initiate the display studies on this equipment. In addition to enabling zero-zero conditions to be studied, the visual display allowed study of the very important transfer problem of breakout under conditions approaching, but not quite, zero-zero.

Before presenting the display development logic and the results obtained to date from the simulator tests of the displays, some description of the simulator itself is of interest. This simulator consists of a closed-circuit television system which projects a picture of a model runway onto a screen in front of the simulator cockpit. Movements of the pilot's controls as he "flies" the simulated airplane are transformed into electrical signals, which are fed into an analog computer. The computer, in turn, controls the relative linear and angular motion between the TV camera and the model runway so that the perspective of the model runway from the simulator cockpit is realistically representative of the perspective of a runway during an actual landing in the airplane being simulated. The aerodynamic characteristics of the simulated airplane are those of a modern large jet transport. Figure 1 is a picture of the pilot's view of the runway, through the windshield of the simulator cockpit; figure 2 is a block diagram of the simulator drive system.

The display as seen from the pilot's seat in the simulator is shown in figure 3. The display is generated on a 7-inch cathode ray tube, the reflection of which the pilot views in a half-silvered mirror suspended in his line of sight through the windshield. For the present tests the image is not collimated.

Pilot's performance in landing the simulated airplane with the two modified forms of the display are being compared on the simulator to pilot's performance in landing with the simulated VFR picture. A summary of the results obtained to date is in a subsequent section of this paper.

Experimental Procedure

The current experiment is designed to analyze simulated landings by three pilots, each using the simulated VFR picture in combination with different displays, cross winds, and initial errors in position with relation to the runway. We are analyzing continuously throughout the approach, flare, touchdown, and part of the roll out those quantities which show the velocity, the position, and the attitude of the airplane. By analyzing the data continously instead of only at touchdown, time histories of an average and a variance for each of the quantities can be obtained. Using these data we are determining not only if there is a difference in end result for the different displays, but also if the pilots cancel out differences between displays by working harder with the displays which are more difficult to use.

Design Logic of Ames Display Studies

The following qualitative description of the moment-to-moment objectives of the pilot during a VFR approach and landing is the basis for the design of a VFR-like display:

1) Find the airport

2) Take gross horizontal aim at general vicinity of airport

3) Start letting down toward general vicinity of airport

4) Monitor and adjust ground track, keeping in mind that horizontal aim must ultimately lie along runway

5) Begin to pay some attention to the point on the runway upon which to touchdown

6) Set up a glide, not too shallow, not too steep, which intersects the ground short of the touchdown point and from which flare to the touchdown point can be made

7) Compensate heading for cross wind so that ground track coincides with runway centerline

8) Monitor and adjust flight path angle, rate of descent, and ground track with increasing precision as ground gets closer

9) Start paying close attention to relative motion of touchdown point

10) Make fine adjustments in horizontal track

11) At proper time, break glide and fly toward touchdown point so as to arrive there as smoothly as possible

12) Attempt to foresee and prepare for control activities peculiar to the impending touchdown

In all except the final step of this rather unprecise procedure the pilot is attempting to ascertain and to adjust to his liking the point on the ground toward which he is flying as well as to orient his path toward it. Of course, the point toward which he wants to fly is determined according to the orientation of the runway relative to him. In the final step just before touchdown, impact point and flight path have become practically unalterable, and the pilot is more concerned with

adjusting the attitude of the airplane relative to its path. The display, then, must be one from which the pilot can infer, as nearly as possible the way he does VFR, those pieces of information necessary to achieve these listed objectives.

A drawing of our first attempt at a design is shown in figure 4. The horizon line behaves essentially as one in the familiar attitude gyro. The runway is indicated by three dots, which represent points on the runway centerline, one at the threshold, another about 25 percent of the runway length from the threshold, and a third at the end of the runway. The point toward which the airplane is flying, the impact point, is a circle. The horizontal and the vertical coordinates of each symbol in the display are functions of the direction and the magnitude of the three-dimensional vector which specifies the position with relation to the airplane of the ground point represented by the symbol. The horizontal coordinate is the quotient resulting from the division of the y-body-axis coordinate of the vector by its magnitude; the vertical coordinate is the quotient of the division of the z-body-axis coordinate by the magnitude. (The magnitude of the vector is the slant range to the point.) The display is scaled so that the angle subtended, at the pilot's eye, by a distance on the display is the same as that subtended by the "real world" distance represented in the display. As indicated in the drawing, the pilot, knowing the scaling, can estimate flight path angle, angle of attack, and drift or sideslip from the relationship between the impact point, the horizon, and the airplane index.

A preliminary, subjective evaluation was conducted to choose a form, or forms, of the display for more extensive quantitative tests. These

preliminary tests led to the modifications of the original design mentioned in a previous paragraph describing the display: the three runway dots of the very first design were expanded into lines, to improve the perspective of the runway (fig. 5), and, subsequently, a height indicator was added for better height and height-rate information (fig. 6).

These modified forms were chosen for further quantitative, experimental evaluation. These choices were based on the opinions of the Ames test pilots who participated in the preliminary evaluations. They feel that representing the runway with lines instead of with dots provides much more and better information, particularly about the horizontal position and direction of travel of the airplane with relation to the runway. The height indicator was added because the pilots were not satisfied with the height and height-rate information implied in the display by, respectively, the distance of the runway end below the horizon, and of the impact point below the horizon (the flight path angle). They feel that the height indicator is much more explicit and compelling, and the information it provides is more easily absorbed.

Operation of the display can probably best be described by a series of pictures. In order to obtain clearer photographs, pictures were taken of a CRT presenting the display rather than of the half-silvered mirror as the pilot sees it. In figure 7(a), the airplane is flying toward a point on the horizon slightly to the right of where the nose is pointing; that is, the airplane is flying straight and level, crabbed into a wind from the left. The runway perspective and position indicates that the

airplane is to the left of the runway centerline and flying away from the centerline, farther to the left of it. Figures 7(b), (c), and (d) show an S-turn to the right at constant altitude, to line up with the runway. The range to the runway is being reduced as the line-up is made, so the runway symbols get larger in the display. Let us assume the pilot wants to approach on a 3° flight path toward the runway threshold, then flare toward the point 25 percent down the runway and touchdown with a 1° flight path. He would fly straight and level, horizontally along the runway centerline until the threshold is 3° below the horizon, as in figure 7(e). Then, he would make the runway threshold the point he is flying toward, that is, begin a 3° descent, as in figure 7(f). As he approaches the threshold along this 3° flight path, the apparent width of runway gets larger, as indicated by the increasing width of the runway symbols. In addition, as range decreases those ground points between the horizon and the impact point move closer to the horizon, as in figure 7(g). If there were indicated in the display any points farther from the horizon than the impact point, that is, nearer to the aircraft they would move even farther from the horizon or, down on the display. This is exactly analogous to the apparent relative behavior of points on the ground during a VFR approach. As the 25 percent runway line approaches 1° below the horizon, the flare is made so that the airplane flies toward that line along a 1° flight path, as in figure 7(h). Now the impact point is between the horizon and the threshold, so the threshold moves down away from the horizon, as in figure 7(i),

until finally it will go out of the display. The 25-percent line stays 1° below the horizon and the runway end moves upward toward the horizon until, as in 7(j), the pilot has de-crabbed so that airplane heading and ground tracks coincide at touchdown. This last maneuver is rather tricky and requires a precise estimate of time-to-go to touchdown, more precise than could be estimated from the slow rate of movement of the runway end up to the horizon. To improve height and height-rate information, we added a height indicator, shown in figures 6(a), (b), and (c); the landing conditions are the same as in figures 7(h), (i), and (j). The vertical distance between the height dash and the impact-point circle is the height above ground. A satisfactory scaling appears to be such that one foot of height is equal to about 0.002 radian of angle subtended at the pilot's eye. The height dash is somewhat analogous to the shadow of the airplane on the ground - it runs along the ground below the airplane, until at touchdown the shadow coincides with the impact point. It should be pointed out that it is not necessary to make a 3° approach and 1° touchdown as in the example above. The pilot can approach with as steep or as shallow a flight path as he wants to. He can approach toward a point short of the runway and then flare to a point just beyond the threshold. Or he can make a long, shallow, no-flare landing. He can make any type of landing that he can VFR; there is no programming in the display, no commands.

Experimental Results

The test pilots who have used the display during the preliminary development and the setting up of the experimental equipment adapted

readily to it. The analogy to visual conditions is very strong, such that even during unsuccessful simulated landings with the display the pilot was aware of what aspect of the landing was going awry. In general, the display appears to provide very good information for longitudinal control, good when-to-flare information, and allows very good vertical speed control after flare, especially with the height indicator. Lateral control - roll angle and sideslip - seem not quite so good. This may be due to the small size of the display or, in the fixed cab, to the lack of motion cues from rolling and slipping. There appears considerably more trouble controlling Dutch-roll disturbances with the display than with the simulated VFR picture. There is, however, good compatibility with VFR control and judgement techniques, and even though the display is uncollimated and not carefully alined with relation to the simulated VFR picture, the pilots have successfully made simulated IFR-VFR transitions by removing the instrument hood at times very late in the landing and proceeding according to the simulated VFR picture. They report no confusion, because the display gives a good mental picture of what to expect at breakout.

Some representative data which have been taken and analyzed are presented in the following table. The values shown are from 10 landings with the display and 10 landings with the simulated VFR picture by one pilot who was very familiar with the simulator and the VFR picture but had not flown the display before. He made about 8 or 10 practice runs with the display before the data were taken. Data presented are for conditions at the instant of touchdown.

Touchdown Data From 10 Landings by One Pilot

	Simulated VFR		Display	
	Mean	Standard deviation	Mean	Standard deviation
Flight path angle, deg	0.69	0.18	0.37	0.18
Rate of sink, ft/sec	2.4	0.68	1.4	0.68
Bank angle, deg	0	2.7	0	5.3
Sideslip angle, deg	0	0.15	0	0.42
Ground track error, deg	0	0.80	0	1.8
Distance off centerline, ft	0	8.7	0	38
Distance from threshold, ft	6100	730	6400	1600

The mean rate of sink at touchdown is 1 foot per second lower with the display than with the VFR picture. The variability from landing to landing, as measured by the standard deviation, is about the same, however. The variabilities in roll angle, in distance off centerline, and in distance down the runway are larger with the display than with the VFR picture but not so much that they cannot be improved with a few more practice landings and some improvements to the display. This last assumption is supported by the touchdown data from landings made by another test pilot who was familiar with neither the display nor the simulator. His performance tended to favor neither one, and those differences measured were not significant according to statistical tests.

Future Experiments

After performance with the display in its present form has been compared thoroughly against the simulated visual flight conditions,

modified or more complex forms of the display will be studied and compared. We plan to test effects of adding redundant information to the display. We will investigate quickening (the addition of lead information) of the individual elements of the display and of the entire display. We can compare different locations for the display - panel or head-up - and collimation versus no collimation. The last two factors have been well investigated by the British Royal Aircraft Establishment as reported in their Technical Note I.A.P. 1132 by J. M. Naish. But we'll take at least a quick look at the effects of placement and collimation on our particular display. We will attempt to define the optimum scaling. We plan also to test the value of director information and maneuver limit information to the display but, as stated before, we hope such computed information proves unnecessary. The display configurations which appear usable will be compared during transition from IFR to simulated VFR conditions. The effect on display requirements and landing performance of combining degrees of automation with manual control can be examined.

In accepting or rejecting a proposed configuration of display for quantitative experiment we will rely heavily upon the opinions of the program test pilots. Their experience flying both airplanes and the simulator has given them some feeling for the importance to a particular investigation of differences in handling between airplanes and the simulator. Concurrently with the display program, components for the airborne system should be undergoing development and, ideally, be available for flight testing forms of the display which looked promising on the simulator.

COMPONENTS FOR THE AIRBORNE SYSTEM

The airborne equipment for investigating the all weather landing system consists of several individual systems which combine to supply suitable inputs for the pilot display system. For the research program it was expeditious to use existing equipment even though the combined size and weight exceeded the acceptable limits for an ultimate system. This has been done with the view that technological advances will further improve and reduce the size of any system which proves feasible with the presently available equipment. The fact that considerably more equipment will be necessary to study various system configurations than would be necessary for a single system has led to a rather generous allowance for size and weight of the research equipment.

By the nature of the problem there are a number of constraints on equipment. Electromagnetic devices such as radar can be used provided they radiate from on board the landing aircraft. A minimum of associated equipment, such as corner reflectors or a coded radar beacon, can be mounted on the ground. All the normal aircraft on-board sensors can be used. All computing equipment must be on board.

The basic elements needed for the flight program are the following: a forward-looking radar for azimuth, elevation, range, and range rate to the touchdown point; a radar altimeter for absolute height above the terrain; inertial elements for certain aircraft motions and for smoothing the radar altimeter data; a flexible on-board digital computer to process data from the sensor equipment and generate pilot display data; and, suitable pilot display devices.

The equipment being procured for the flight tests consists of production items which represent recent designs of proven reliability. The specific equipments consist of a self-tracking, multimode, airborne fire-control type radar which will be used as the forward-looking radar, a precise radar altimeter which is accurate to a foot or so of altitude, the Verdan II digital computer, inertial rate of descent equipment which is monitored by the radar altimeter, and special pilot display devices.

The forward-looking radar is a production model of a radar system used on military aircraft. It is an X-band radar capable of self-tracking in azimuth, elevation, and range on either a corner reflector or a beacon. A beacon target is the preferable since it can be used to effectively prevent the radar locking on nearby strongly reflecting targets. A corner reflector can be used only if it can be located in a relatively clear area. The radar has several modes in addition to the self-tracking mode, some of which will be useful for the all weather studies and some of which will not. It has a search mode which should be of assistance during initial approach and beacon acquisition.

The radio altimeter is a standard design of proven reliability. It has an accuracy of 2 feet near the ground and about 5 percent of altitude at its maximum range. Its minimum range is sufficiently short to allow its use through the landing to actual touchdown.

The on-board computer is a flexible digital computer of an airborne type. It combines a general purpose computer with a differential analyzer section, both under the control of an internally stored program. It has a 27 bit word length and a 5632 word storage. The computer weighs 180 pounds and occupies about 3 cubic feet.

The inertial rate of descent equipment consists of an integrating type of accelerometer monitored by the radar altimeter so as to cancel the effects of gravity and accelerometer drifts. This equipment will be used to present an accurate indication of the aircraft's rate of descent. The instrument has a range from 0 to ±50 feet per second and an acceleration range of 1 ± 1 g.

The flight hardware will be used in conjunction with ground studies to check and improve promising techniques. Normally, after a system is generated from an analytical study it will first be checked on ground-based simulators. The more promising techniques will be worked into the flight equipment through suitable equipment interconnection and programming of the on-board digital computer. Flight checks will then be conducted with modifications to the equipment and to the computer program being made as the flight program progresses. It is to be hoped that the studies using this rather complex equipment will separate out the essential quantities which require measurement. Once this has been done, it is probable that a small highly reliable piece of equipment could be designed to collect this essential data and process it for the pilot's display.

CONCLUDING REMARKS

Although it is far too early in the program to state unequivocally that the projected zero-zero system can be realized successfully, it does appear that certain fundamental requirements can be met.

1) Although aircraft can be landed with a limited view two-dimensional pictorial presentation, a significant amount of information

(as yet undefined) present in the real world is lacking in the two-dimensional presentation. Therefore, compared to a VFR landing, the pilot must work harder to assess the progress of the landing, and the end result is more unpredictable.

2) Symbolic displays can be devised which include at least some of the important information lacking in the two-dimensional pictorial display and, though symbolic, allow the pilot to respond to the information and fly the airplane essentially as he does VFR. It appears likely that such a display can be developed so that with it a pilot can make routine zero-zero landings without the necessity for computed director information. This implies also the additional ability to monitor automatic landings.

3) System studies show that equipment required to generate the symbolic displays is available in a form that enables an almost completely on-board system. On the basis of the work completed to date it appears promising that the NASA Ames program will lead to a successful flight demonstration of a manual on board zero-zero landing system. Systems studies show that there already exist equipment with which the symbolic display can be generated and which is small and light enough that the system can be almost entirely airborne.

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Figure 1.- The flight simulator and the simulated cockpit runway.

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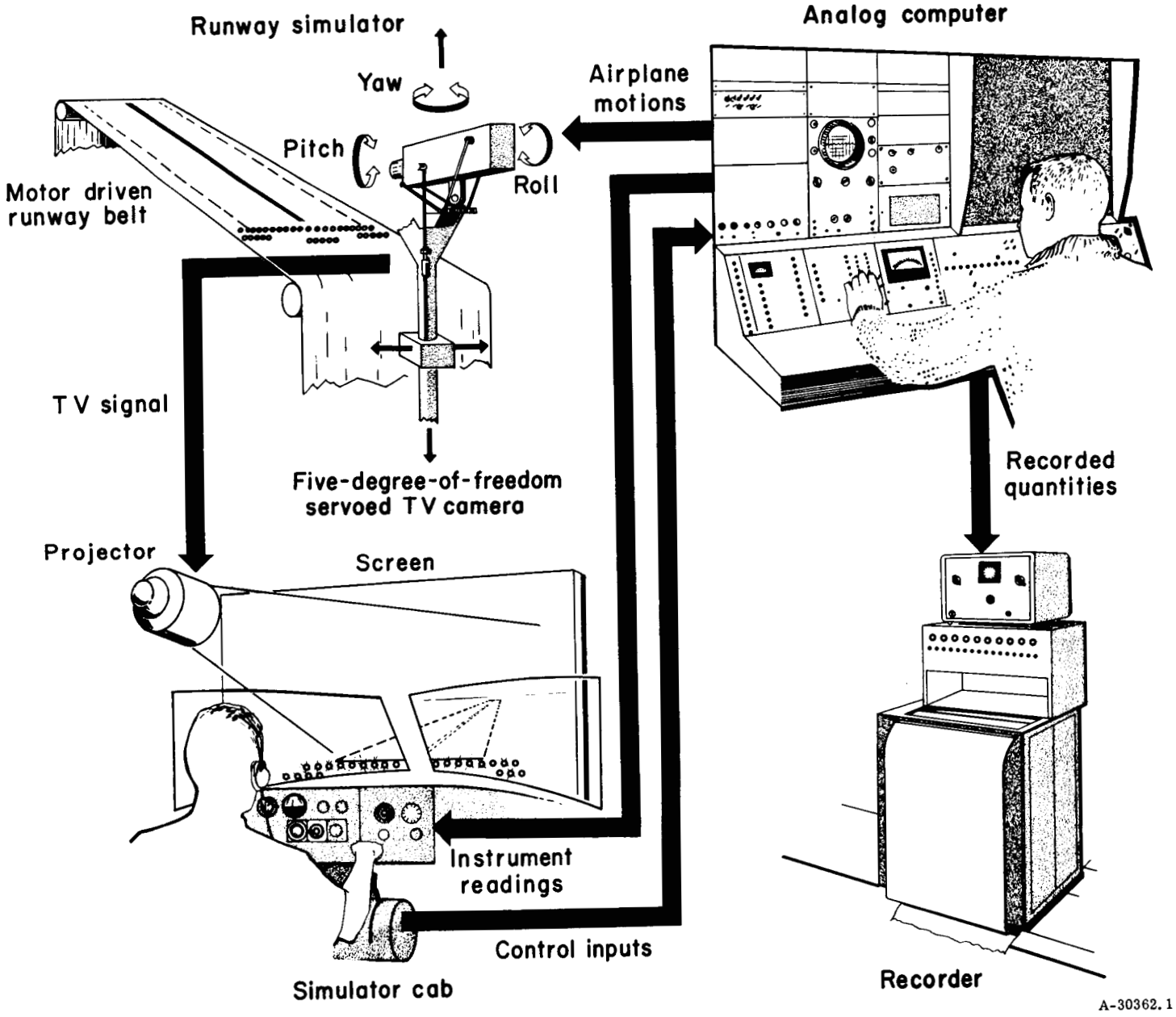

Figure 2.- Block diagram of simulator drive and computing components.

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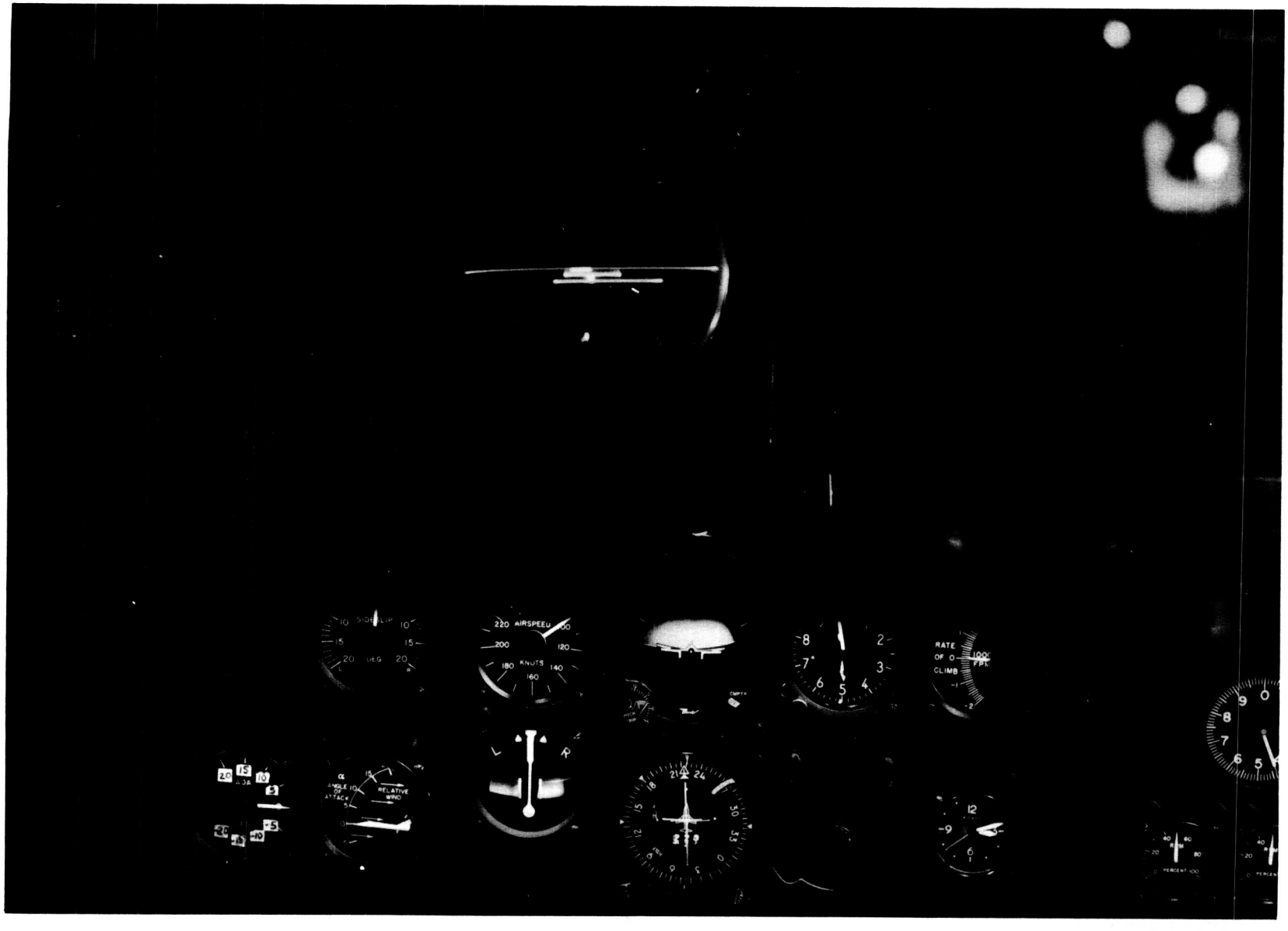

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Figure 3.- The Ames display in the simulator cockpit.

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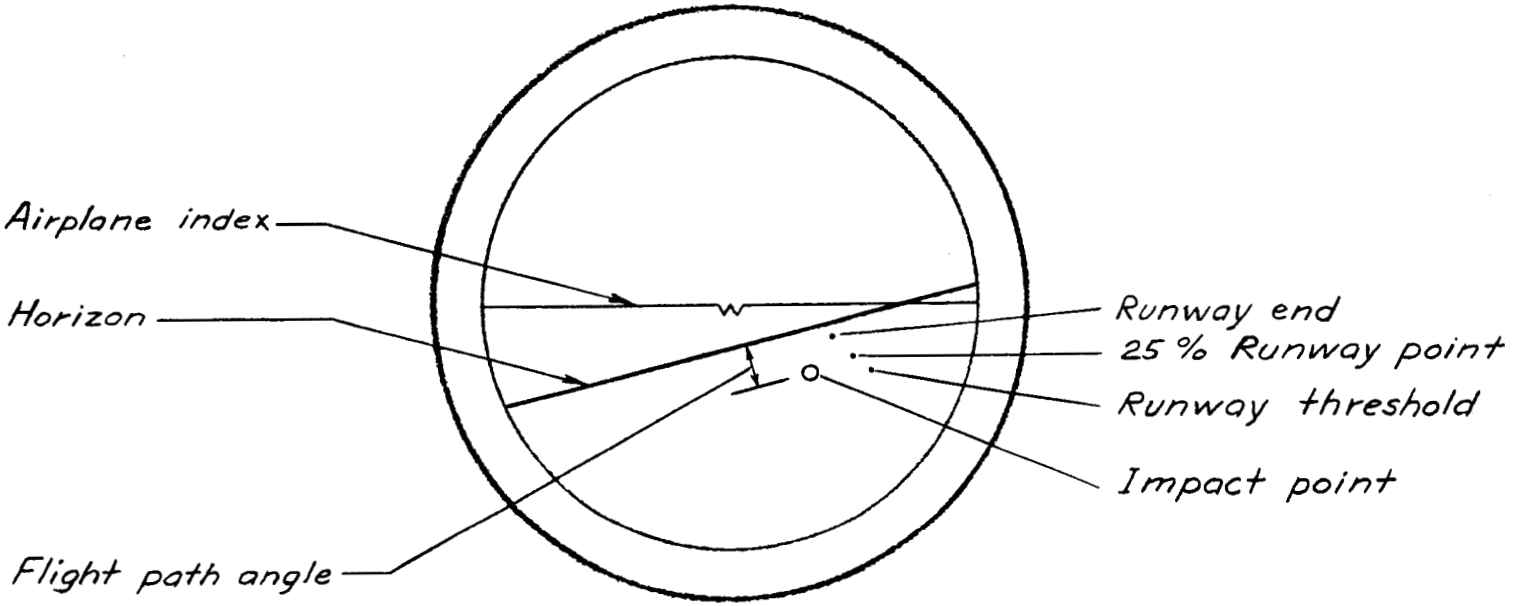

Figure 4.- Original configuration of Ames display.

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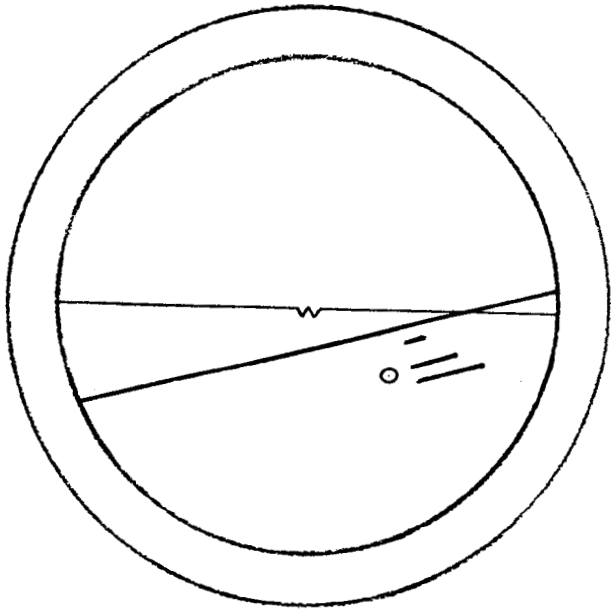

Figure 5.- Modified configuration of display.

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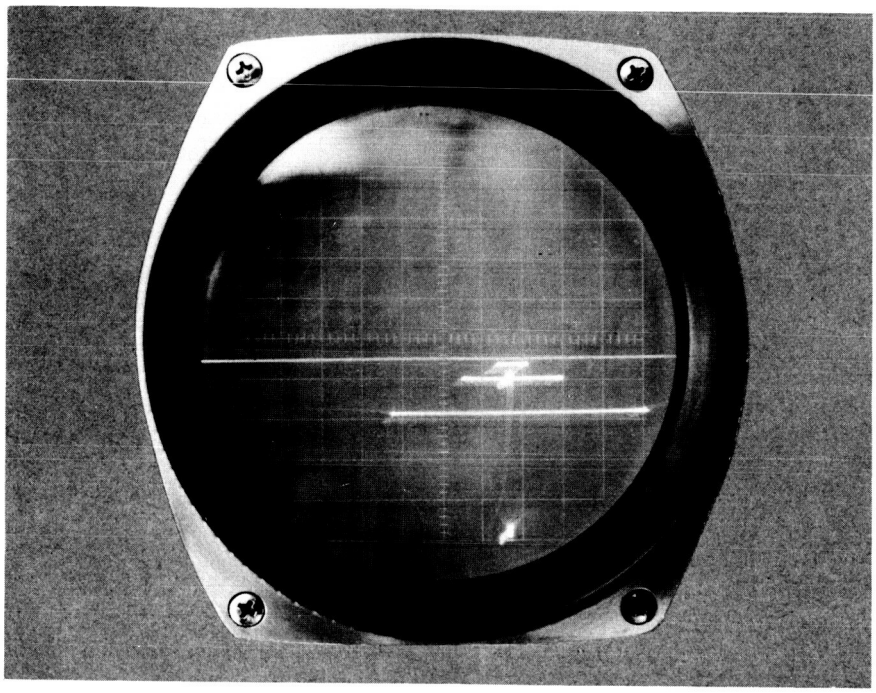

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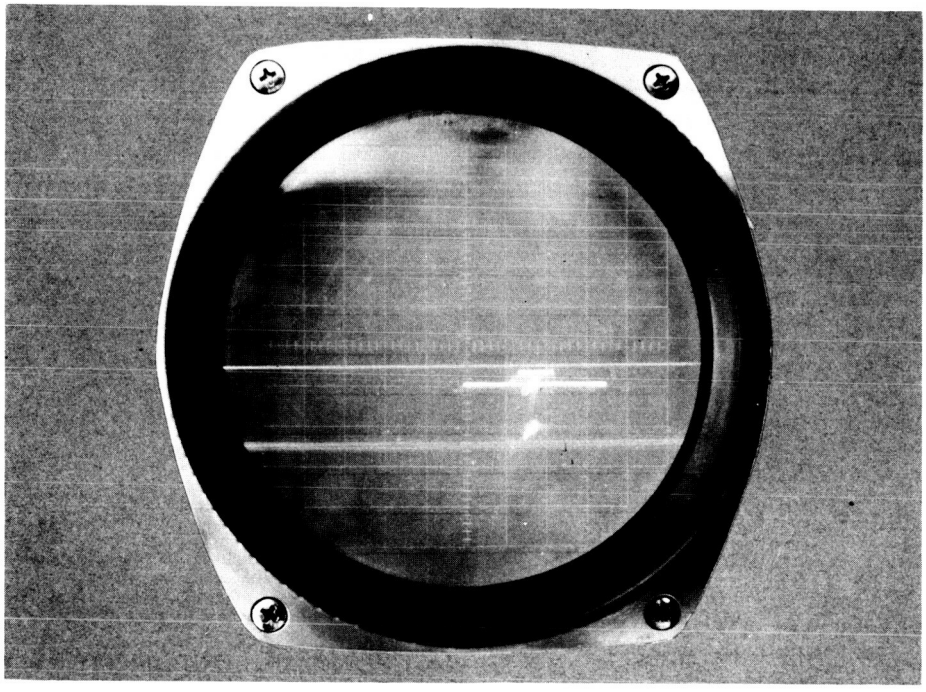
(a)



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(b)

Figure 6.- The display, just before touchdown, showing the height indicator.

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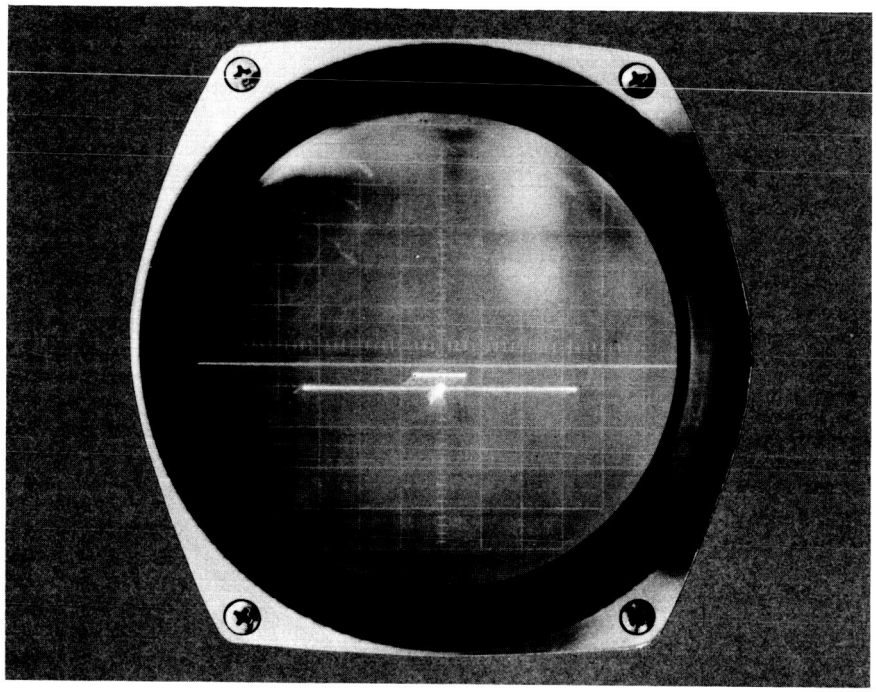

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(c)

Figure 6.- Concluded.

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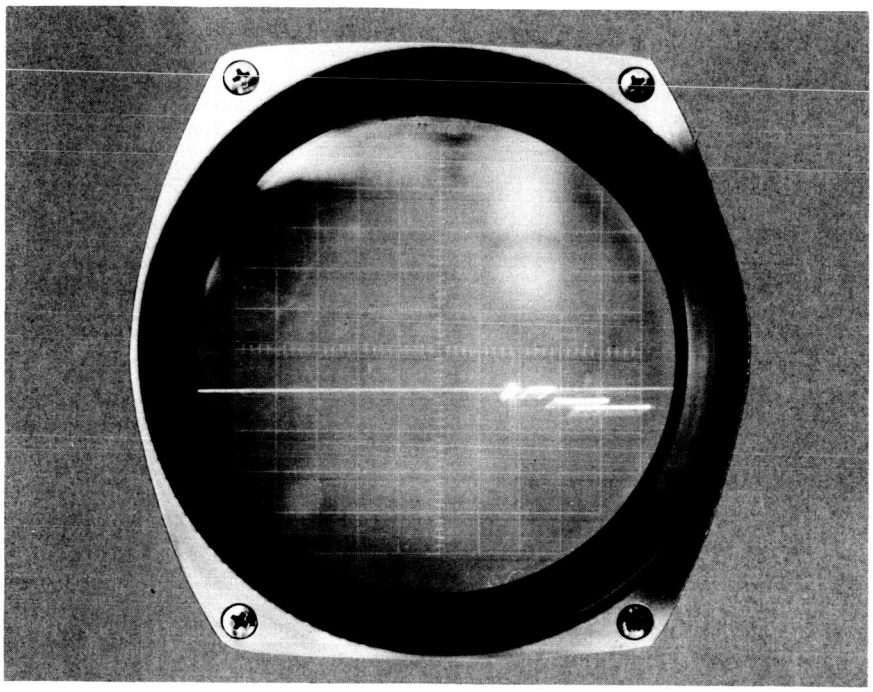
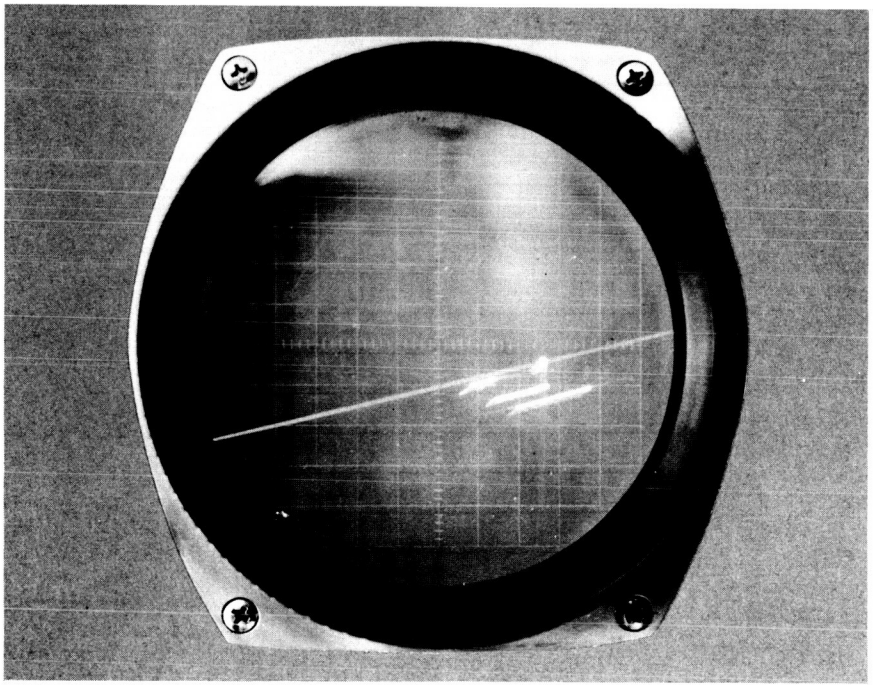


A-30401-5

(a)



A-30401-6

(b)

Figure 7.- The Ames display during an approach and landing.

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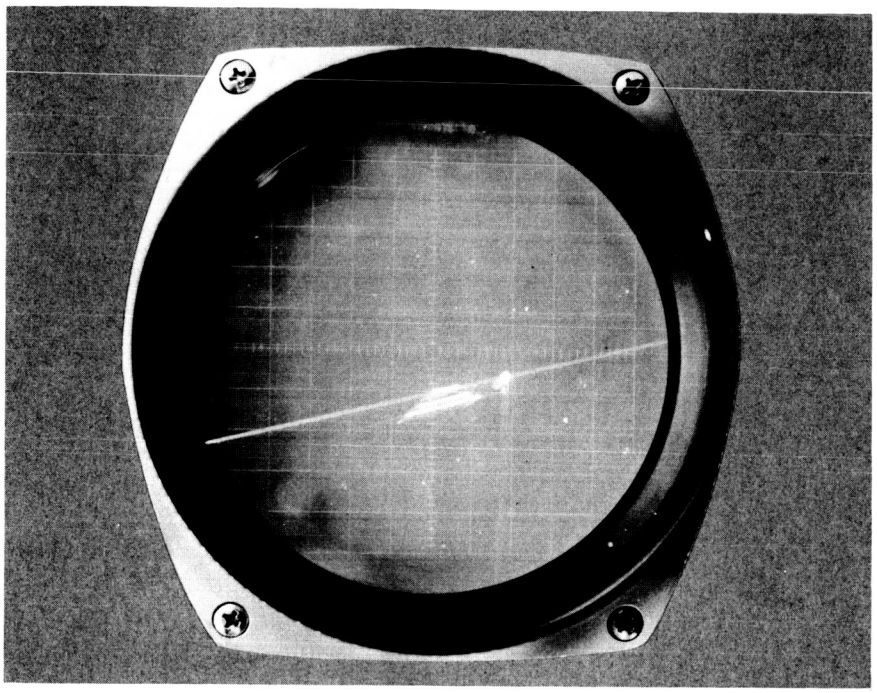
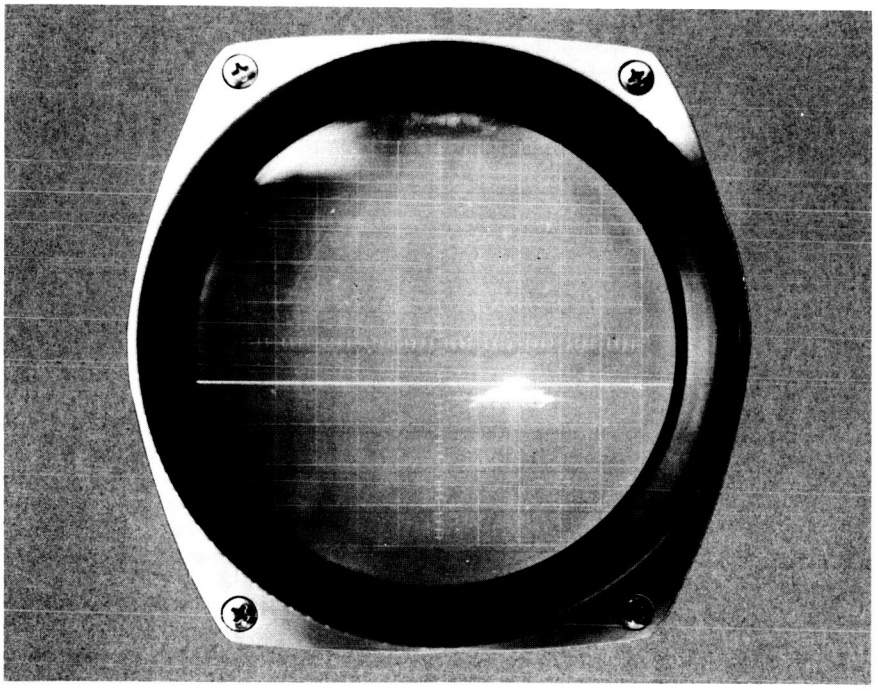


A-30401-7

(c)



A-30401-8

(d)

Figure 7.- Continued.

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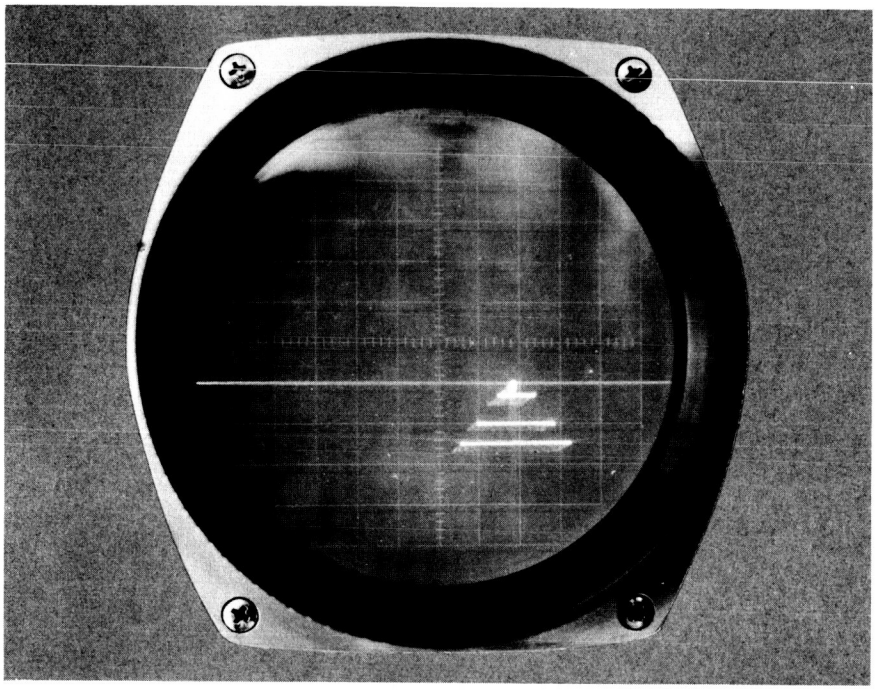
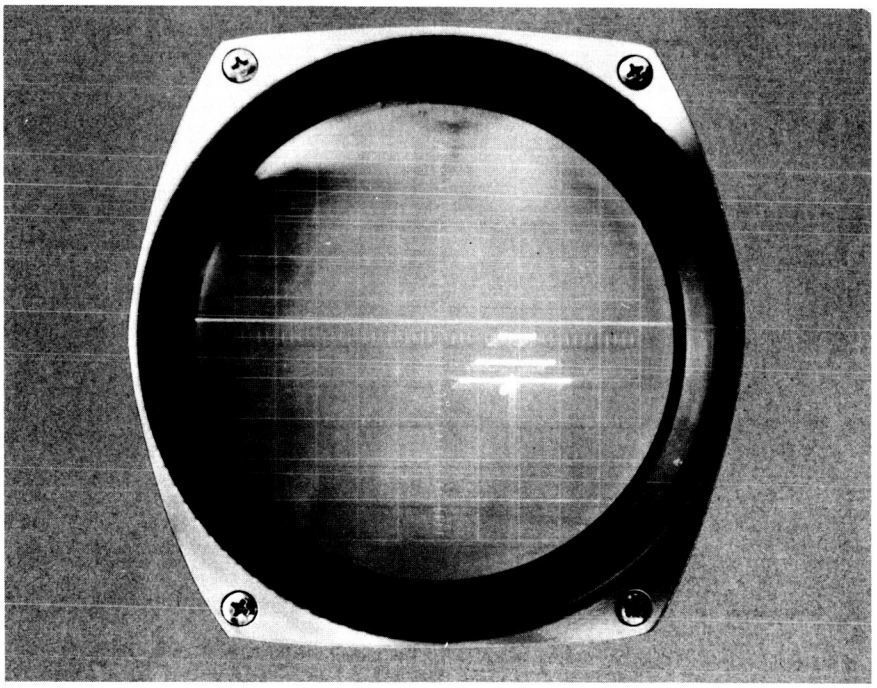


A-30401-9

(e)



A-30401-10

(f)

Figure 7.- Continued.

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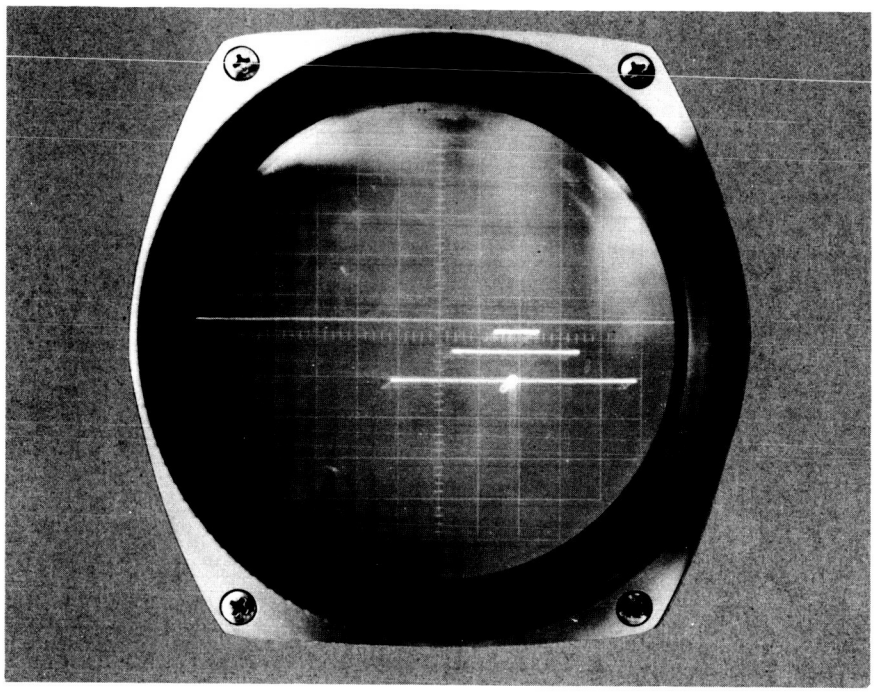
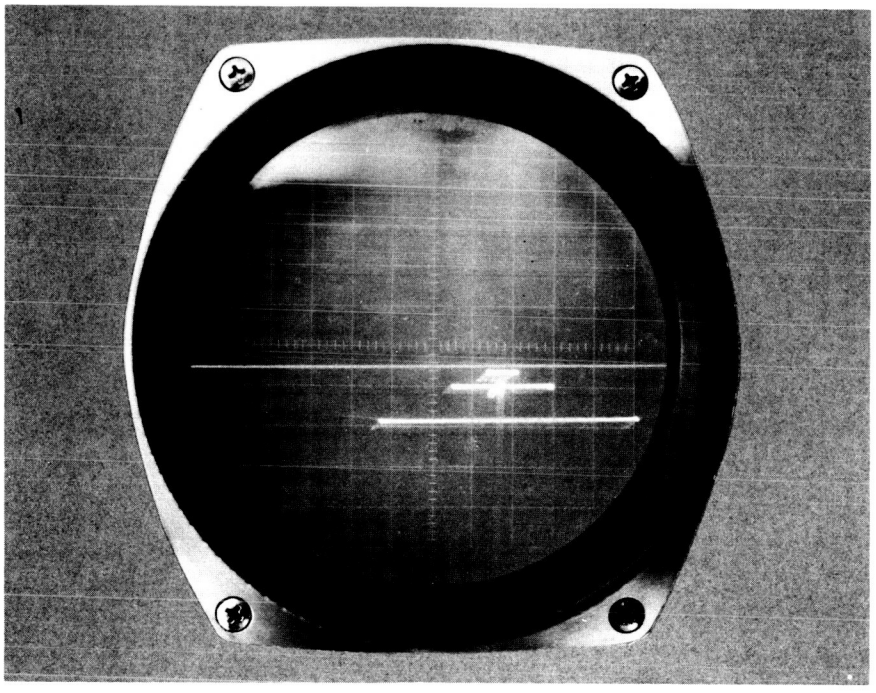


A-30401-11

(g)



A-30401-12

(h)

Figure 7.- Continued.

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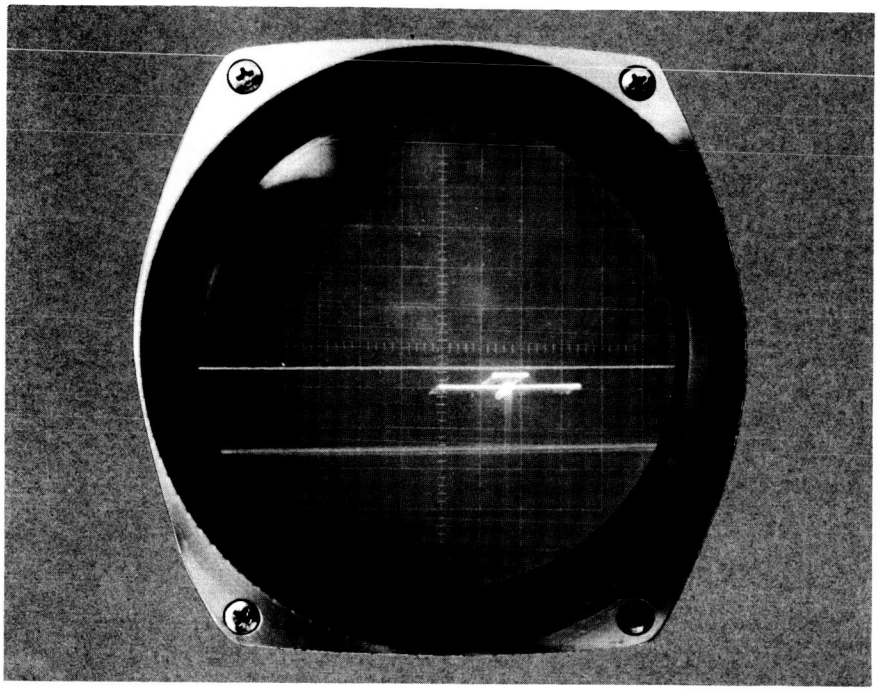
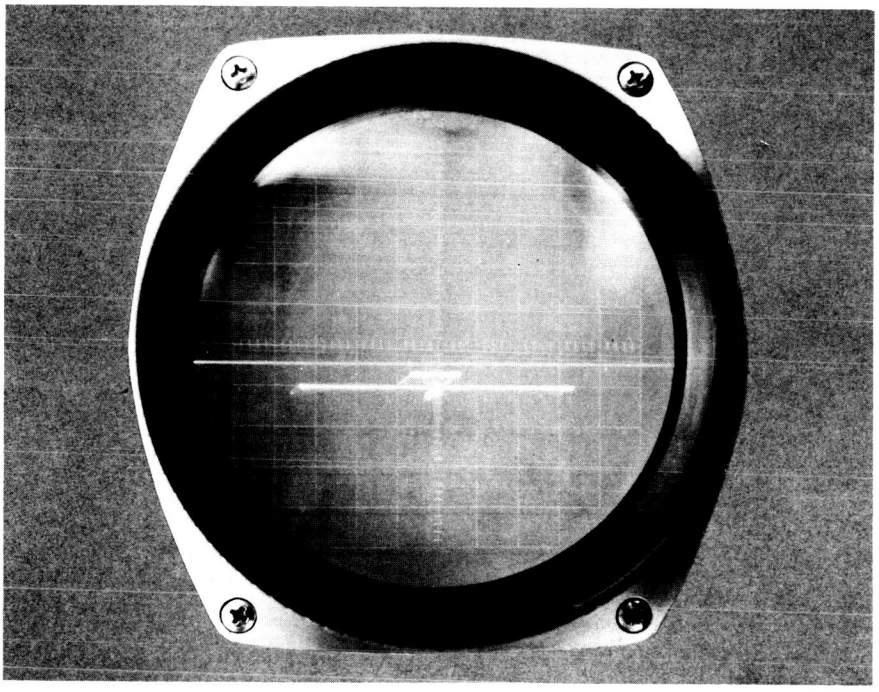


A-30401-13

(i)



A-30401-14

(j)

Figure 7.- Concluded.

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